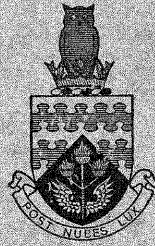


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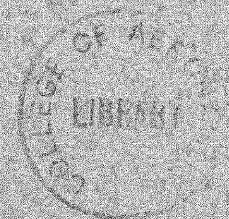


THE COLLEGE OF AERONAUTICS  
CRANFIELD

SUPERCONDUCTIVITY - SOME ASPECTS  
OF THE THEORIES AND POSSIBLE APPLICATIONS

by

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Superconductivity - some aspects  
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S U M M A R Y

Superconductivity is an effect exhibited by certain materials at very low temperatures in which normal electrical resistivity disappears completely. Summaries of the current theories which attempt to account for this phenomena are presented, and various proposals for making use of this effect in practical devices are examined and discussed. Proposals for a programme of research in the application of superconductivity to rotating electrical machines are outlined.



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## 1. The Phenomenon of Superconductivity

Superconductivity is a remarkable state of matter which provides considerable possibilities for applications in science and technology. It is an effect exhibited by certain materials, mainly metals and metallic mixtures and compounds, in which normal electrical resistivity disappears completely at very low temperatures. The highest known temperature at which any material becomes superconducting is 20.1°K; this is the critical temperature of a recently-developed alloy of niobium, aluminium and germanium. Niobium-tin has a critical temperature of 18.1°K and was used extensively for winding early superconductive magnets. In later magnets it was superseded by niobium-zirconium and more recently by niobium-titanium (10.5°K).

Below its critical temperature, a superconductor can be made to revert to the normal or resistive state by the application of an external magnetic field, the threshold value of this being referred to as the critical value and it is temperature dependent.

The transition to the superconducting state of an ideal superconductor is reversible, and in this respect it differs from the transition of an ordinary conductor to a merely perfectly conducting state. It has been found that with an ideal superconductor the magnetic flux is expelled from the interior of the specimen in the superconducting state, irrespective of any magnetic field which may be present either before or after the superconducting transition. This exclusion of the magnetic flux is called the Meissner effect.

## 2. Phenomenological Treatments

Since the discovery of superconductivity by Kamerlingh Onnes over fifty years ago reasonably satisfactory theories have been developed from which a basic, although incomplete, understanding of the effect can be obtained. By accepting a macroscopic description of a superconductor as a body in which the magnetic flux density,  $B$ , and the electric field,  $E$ , are both zero enables a number of observed effects to be correlated and certain electrical and thermodynamic conditions to be deduced. Consideration of surface energies enables progress to be made, particularly for dealing with problems of mixtures of the normal and superconducting phases which occur in the intermediate state.

Phenomenological treatments also dealing with the macroscopic characteristics have developed along two main and complementary approaches. In both an arbitrary postulate is made in an attempt to explain the experimental facts. F. and H. London (1935) derived a model based on a relationship between the current density and the vector potential associated with a magnetic field, which in effect, generalised the equations

$$B = 0$$

$$H = 0$$



These equations provide an adequate description of the interior of a macroscopic superconductor, and Londons' postulation, which introduces the concept of penetration depth, enables the region close to the superconducting boundary to be included as well.

The complementary approach of Gorter and Casimir (1934) is based on the superconducting transition being of the second kind, and that below the transition temperature the entropy of the superconducting state is always lower than that of the normal state. To account for the increase in the degree of order as the temperature becomes lower, they introduced the idea of the 'two-fluid' model in which below the transition temperature the metallic electrons are divided between two dependent groups at different energy levels. The electrons at the lower energy levels form the 'superconducting' group, while the remainder at the higher energy levels remain normal. For the superconducting transition to be of the second kind it is necessary for the groups or phases to be dependent. The choice of function relating the two phases is arbitrary but is chosen to suit the experimental facts. Later work has shown that the equations of the London Theory and the Two-Fluid Model are exact for only certain limiting conditions, but even so they provide a useful means of explaining many aspects of superconductivity. Their limitations become serious in problems concerned with size and surface effects.

Pippard, however, (in 1950, 1951 and 1953) has shown how certain of these effects can be taken into account on the basic London model by allowing for the finite coherence of the superconducting wave functions (the Pippard non-local theory). Complementary to the non-local theory, another method of treating the coherence of the superconducting wave functions, or order parameter, was developed by Ginzburg and Landau (1950). Their method specifically allows for spatial variations in the energy gap and in the density of the superconducting electrons. The Ginzburg-Landau model is able to treat a superconductor in an external field of approximately the same magnitude as the critical field in any temperature range, and it is from this ability that its main usefulness derives.

### 3. Microscopic Theory

On the microscopic scale, the generally accepted theory is that due to Bardeen, Cooper and Schrieffer (1957). In 1956, Cooper showed that pairs of electrons could condense into a lower energy state than electrons in the normal state, provided that there was some attractive force between the electrons in each pair. The attractive force could be extremely small however, and Bardeen, Cooper and Schrieffer showed that the attraction between the two correlated electrons is due to electron-phonon interaction, which in qualitative terms may be considered as due to the lattice distortions produced by two electrons. The BCS theory supposes that this attractive interaction takes place between electrons with opposite spins, and having equal and opposite momenta. These 'electron pairs' can carry current, but unlike single uncorrelated electrons, they are not scattered to lower energy states by moving through the lattice and giving up energy to it. Thus the

electron pairs can carry current which sustains no loss. The basic BCS theory has undergone several refinements, and several objections to it have been raised from time to time, the latest being by Fowler, et al., at Los Alamos, (October, 1967). Nevertheless, the BCS theory is very successful in explaining the behaviour of an idealised superconductor.

#### 4. Type II Superconductors

On the macroscopic theories it is necessary to consider the surface energies at the boundary between the superconducting and normal phases; London showed that the complete Meissner effect does not lead to a state of lowest energy for a superconductor unless such a boundary energy exists. In the absence of positive surface energy, it would be possible for an ideal bulk superconductor to split into alternate normal and superconducting regions at some field below the critical value. The normal regions would allow the field to penetrate and thus lower the magnetic energy, but except for special cases in the intermediate state this does not occur. The surface energy is closely related to the range of coherence of the superconducting wave functions and if the range of coherence is less than the London penetration depth, negative surface energy results. This occurs in an important group of superconducting materials, mostly alloys, referred to as 'negative surface energy', 'hard' or 'type II' superconductors. In these, the field can penetrate deep into the superconducting regions and the material will divide spontaneously into a mixed state at a field below the critical value. The principles of type II superconductors were developed by Abrikosov (1957) and Gor'kov (1959) based on the Ginzburg-Landau theory. Goodman (1961) applied this work to high-field superconductors, and Kim (1963) and Anderson (1962) proposed models to explain the flux-flow and flux-creep phenomena. Bean (1962, 1964), by assuming that the critical current density was independent of the flux, proposed the critical state model which enables the macroscopic internal fields and induced currents inside an imperfect type II superconductor to be determined.

Although type II superconductors are suitable for high magnetic fields, they have certain disadvantages which may be broadly classed as a.c. losses and flux instabilities. The magnetisation of a type II superconductor is not a reversible process and a loss is sustained during cyclic magnetisation. Bean (1964) and others have developed expressions for the energy loss in terms of their magnetisation models, and considerable experimental work on a.c. losses is also being carried out. These losses prohibit the use of present type II superconductors in nearly all applications where alternating currents or fields would be present. Flux instabilities, or flux jumps, are due to the lack of a state of equilibrium. In the critical state each pinning centre is about to release a fluxoid, and any slight mechanical, thermal or electrical disturbance is likely to cause some flux unpinning. In superconducting solenoids flux instabilities give rise to phenomena known as 'training' and 'degradation', although cladding of the superconductor in, for example, copper greatly reduces these effects; this was first proposed by Kunzler (1961). Fully stabilized composite conductors were developed by Stekly who presented an analysis of such conductors subjected to externally

applied fields (1965); analysis of the thermal considerations was carried out by Kremlev (1967). Alternative means of stabilization, (enthalpy stabilization) have been proposed by Moon (1967) but hardly any publications have appeared to date. Enthalpy stabilization (and other methods) require theoretical investigation, but without access to special facilities for the fabrication of composite superconductors, it would not be possible to undertake the verification of theoretical analysis.

## 5. Applications

From the reviews of the theories of superconductivity and of the properties of type II superconductors in the foregoing, it is seen that the means exist to attempt to apply superconductivity to practical situations. The current theories by no means give a complete understanding, and considerable basic research into the physics of superconductivity and the science of superconductive materials is still required to be done. However, as there is now a considerable accumulation of literature on the subject and much of the basic cryogenic equipment and superconductive materials are available at short notice on a commercial basis, it seems that more effort should be placed on investigating practical applications of the phenomenon. To date, applications proposed include computing and switching elements, bolometers, heat valves, small signal amplifiers and microwave mixers and demodulators (see review by Newhouse (1964)); such devices have not reached a commercial stage. One area in which practical use is made of type II superconductors is for the production of high magnetic fields for devices such as masers, lasers, bubble chambers and particle accelerators. The design of such superconducting magnets is becoming an established procedure and several publications on the subject have appeared (Kolm, Lax, Bitter, et al. (1962), Guban (1963), Boom and Livingstone (1962), Wood (1962), and Thomas and Bright (1966). Requirements for fields in excess of  $5 \text{ Wb/m}^2$  over volumes of several cubic metres exist in MHD power generators and Chester (1965) has shown that superconducting magnets are necessary if acceptable generation efficiency is to be achieved. Similar requirements for a marine propulsion system using a current passed through the water across the magnetic field would exist if such a scheme were to be developed. Initial calculations and preliminary tests indicate the feasibility of such a scheme if the problem of water ionization and electrolysis could be overcome. Numerous schemes have been described for superconducting bearings, suspension systems and levitation (for example, Simon (1953) and Buchhold (1961)) and some are in operation in classified military applications. Flux pumps, as alternative means of producing high magnetic fields have been suggested by Swartz and Rosner (1962), Laquer (1963) and others (van Beelen et al., review (1965)), but the experimental results published so far, are disappointing.

It is in the field of electrical power generation and transmission that the attractiveness of loss-less current conduction is most apparent. Unfortunately, the a.c. losses are precluding the use of type II superconductors at present in cables and transformers. Wilkinson (1963 and 1966) has carried out a detailed analysis and concludes that in neither power transmission by superconducting cable nor transformation by superconducting windings would

the savings in costs warrant the constructional and operational complexities entailed in deep refrigeration. With further research, this conclusion could well be reversed in the next few years, particularly if a superconducting rectifier, proposed by Olsen (1958) and corresponding inverter could be developed. This would make a system of d.c. transmission comprising compatible components an attractive proposition.

## 6. Application to Rotating Machines

Although a considerable amount of effort is being put into the application of superconductivity to cables and transformers, and a not insignificant number of papers written on the subject, the same would not appear to be true of rotating electrical machines, but it is in this field that the immediate prospects are brightest. The obvious way of applying superconductivity to a rotating electrical machine is to replace the iron-cored electromagnets in a conventional type by air-cored superconducting magnets. This has been carried out by Stekly and Woodson (1966) who constructed and tested an 8 kVA, 400 c/s alternator. Design studies have also been carried out (Woodson, Stekly, et al., (1964, 1966) and show significant gains in compactness at powers above 100 kW. They also put forward proposals for a 1000 kVA turbo-alternator set and estimate a specific weight of 1.85 lb/kW including the gas turbine, generator and refrigerator. This is comparable with the specific weights of current aircraft conventional alternators for the alternator only, but in smaller ratings. Volger and Admiraal (1962) proposed a new principle for a superconducting generator and various improvements have been suggested by Wipf (1964) and Sass (1964). Machines using this principle can be regarded as flux pumps and are essentially for generating very high current at very low voltages. The most promising type of machine, however, appears to be the disc type of homopolar machine. Mueller (1964) shows such a machine to have a specific weight which is approximately 12 times more favourable than that of a conventional type and to have a significantly higher efficiency. In aerospace applications where cryogenic fuels, and in particular liquid hydrogen are present, full advantage can be taken of this improved performance. Where a high-speed turbine expansion refrigerator is included, the weight of the superconducting machine scheme is increased to one quarter of that of an equivalent conventional machine. In the industrial field, for which little published data are available, it appears possible that for very large d.c. drives, (in excess of 10,000 h.p.) the superconducting motor including its associated refrigeration plant will be competitive on a cost basis, and certainly be only a fraction of the weight. D.C. generators of the same order of power rating appear equally feasible, and if successful, could well bring about drastic changes in power generation in conjunction with superconducting transmission cables. Such generators would also make the marine propulsion scheme mentioned earlier much more attractive.



## 7. Research at Cranfield

Laboratory facilities at Cranfield to date comprise the installation of a helium gas-recovery system and the acquisition of basic equipment for superconducting experiments; a limited quantity of superconducting wire has also been purchased.

The proposals for an initial research programme are as follows. Rapid control of the field in superconducting machines is a general problem and the initial aim of the research proposed is to examine the properties of superconducting coils to determine the important factors in limiting the rates at which fields produced by them can be changed. Very closely associated with the rate at which the field produced by a superconducting coil can be changed is the stabilization of the superconducting wire itself. Resistance, or Stekly, stabilization is now well understood, but enthalpy stabilization has so far received only cursory treatment. It is therefore proposed that some aspects of enthalpy stabilization will be included in the investigation.

It is proposed initially to endeavour to modify Hancox's method of calculating the a.c. losses in Type II superconductors based on the London and Kim approximations in order to estimate the heat produced by a ramp function of current; various values for the maximum value reached will be used up to nearly the critical value. By employing Kremlev's model for the internal thermal resistance of a superconductor in a normal matrix it should be possible to obtain approximate estimates for the heat transfer inside the composite and across the composite/liquid helium interface, and so enable the temperature rise of the superconductor due to the ramp current to be obtained approximately. The effect of the characteristics of the ramp function on the temperature rise can then be investigated and limited so that the field-dependent transition temperature is not exceeded. The principle theoretical factors affecting the maximum rates and magnitudes of transport current changes which can be applied without the superconductor going normal should then be apparent, but some technological considerations may have to be taken into account as well; also other shapes of single and multiple current pulses can be considered, and the effect of decreasing the transport current.

Depending on the resources available, it is proposed to carry out tests on composite superconducting wire samples and small coils in liquid helium to measure the superconductor losses during rapid changes of current. The samples will be tested under different conditions affecting the thermal environment of the superconductor such as the thickness of the copper matrix and electrical insulation on the wire. Attempts will be made to verify the theoretical analysis carried out. The superconducting wires will be niobium-zirconium and niobium-titanium alloys with copper coatings, and possibly other cladding materials as well, such as lead, indium, cadmium, aluminium and silver. It is anticipated that smaller diameter strands in the superconductor will produce lower losses during changes in current and this effect will also be investigated.



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### Schematic Representation of Relationship between Principal Theories